PETRO

Plants Engineered To Replace Oil

Yield Workbook Webinar

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June 23, 2011

Introduction---PETRO FOA Yield Workbook Webinar

The purpose of the Yield Workbook Webinar is to:

- Facilitate the Applicant's completion of the Yield Workbook for the PETRO FOA by:
  - Clarifying instructions provided in the Yield Workbook template and the PETRO FOA for completing the template. Please refer to ARPA-E's website (https://arpa-e-foa.energy.gov/) to download the PETRO Yield Workbook template and see Section IV.C of the FOA for additional instructions.
  - Illustrating the methodology that should be utilized to prepare the Yield Workbook
  - Provide clarification around the derivation of Table 1 (See Section I, Page 10) in the PETRO FOA

What are the Ground Rules?

- Applicants may ask questions about, or request clarification on, the methodology that should be utilized to prepare the Workbook
- All questions must relate to the Yield Workbook
- All questions must be submitted in writing to ARPA-E-CO@hq.doe.gov during or after the webinar
- The ARPA-E Contracting Officer and ARPA-E Program Director may elect to respond to questions during the webinar or post answers to questions on PETRO's FAQ web page located at http://arpa-e.energy.gov/About/FAQs/FundingPETRO.aspx

What are the Ground Rules? (cont.)

- The webinar does not in any way change the terms and conditions of the PETRO FOA and has no relationship to any other previous or current ARPA-E FOAs
- Keep phones on mute to avoid background noise during the webinar
- No audio/video recordings or transcription of this webinar are permitted. The webinar will be recorded by ARPA-E and will be available until the Full Applications are submitted.

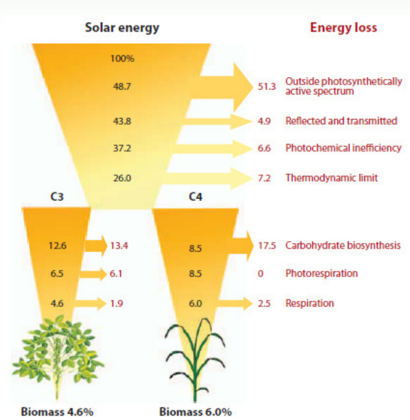
  Instructions on how to access the recording will be sent to Applicants after the webinar

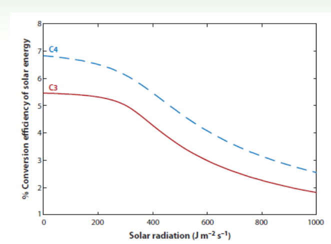
Motivations

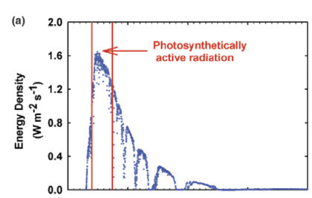
Our Process

Your Process

Energy efficiency measurements are abstract, highly variable, and provide only a snapshot of possible performance





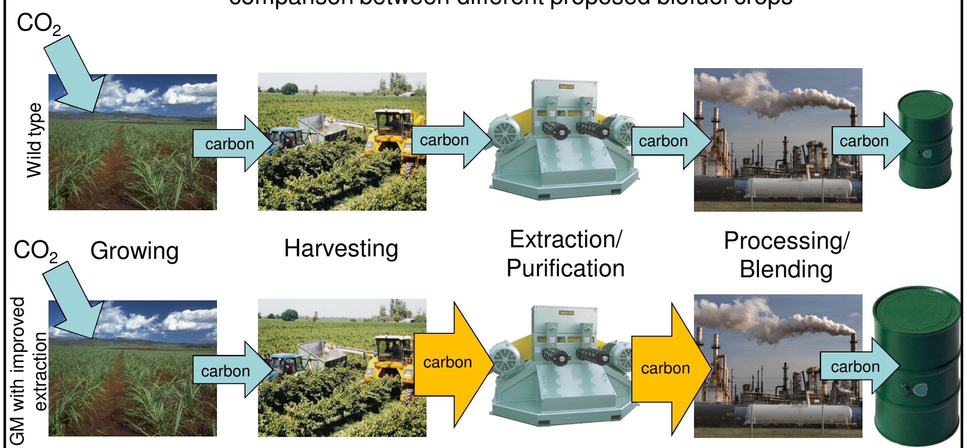


Comparison between different crops in different conditions/climates is difficult

Source: Zhu et al. *Current Opinion in Biotechnology (2008) 19: 153-159.*

Determining energy yields by tracking carbon allows for more robust comparisons between agricultural crops

This process follows a tangible quantity, mass, from start to finish, facilitating comparison between different proposed biofuel crops



Motivations

Our Process

Your Process

Table 1 from the PETRO FOA

Table 1: Carbon flux from atmospheric CO_2 for current biofuel crops

[NOTE: Only carbon is counted as part of weight.]

	Maximum Photosynthetic Rate A_n 50 $t_C \cdot ha^{-1} \cdot y^{-1}$ [10] [based on carbon, mw=12]					
	Maize (*Midwest*) [11, 12, 13, 14, 15]		Soybean (*Midwest*) [11, 16, 17, 18, 19, 20, 21]		Sugarcane (*LA, TX, FL*) [22, 23, 24, 25, 26]	
	$t_C \cdot ha^{-1} \cdot y^{-1}$	Yield	$t_C \cdot ha^{-1} \cdot y^{-1}$	Yield	$t_C \cdot ha^{-1} \cdot y^{-1}$	Yield
Captured	7.7	15%	3.1	6.3%	24.	48.%
Harvested	3.9	7.8%	1.3	2.5%	16.	32.%
Purified	2.7	5.4%	0.38	0.77%	7.7	15.%
Processed	1.5	3.0%	0.34	0.69%	4.0	8.0%
Final Energy Content ($GJ \bullet t_C^{-1}$)	52 (Ethanol)		50 (FAME)		52 (Ethanol)	
Overall Fuel Yield ($GJ \bullet ha^{-1} \bullet y^{-1}$)	79		17		207	

Where did this come from?

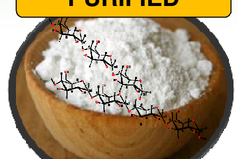
Carbon efficiency in corn grain ethanol production

See PETRO Yield Workbook for detailed breakdown in the 4 worksheets

HARVESTED

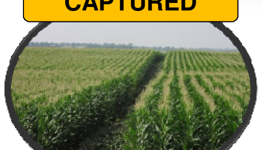
3.9 $t_C \cdot ha^{-1} \cdot y^{-1}$

PURIFIED



2.7 $t_C \cdot ha^{-1} \cdot y^{-1}$

CAPTURED



7.7 $t_C \cdot ha^{-1} \cdot y^{-1}$

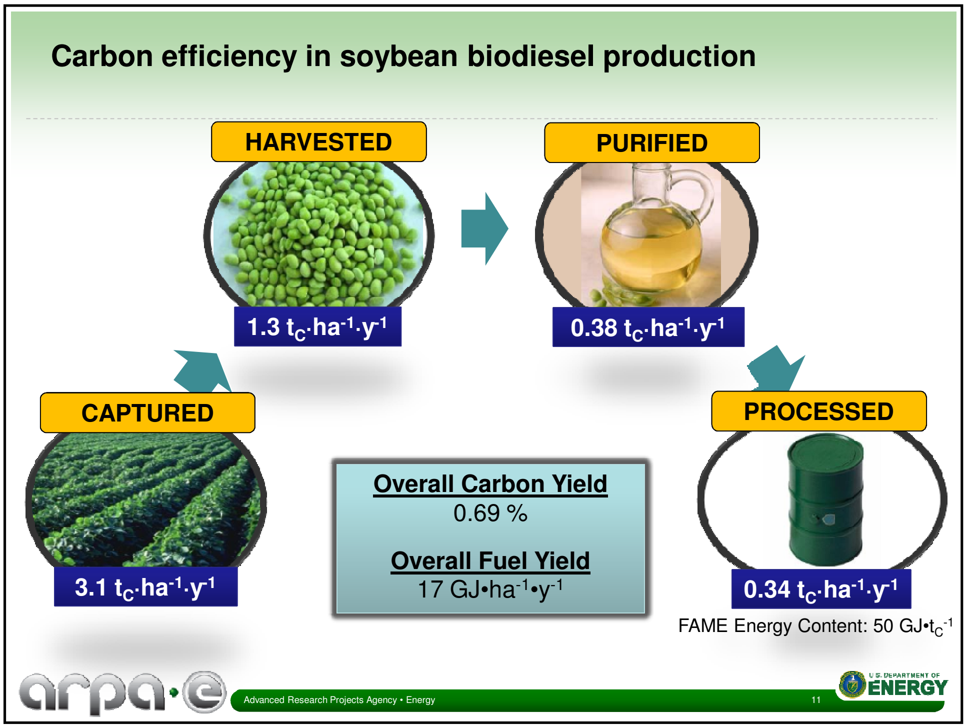
Overall Carbon Yield
3.0 %

Overall Fuel Yield
79 $GJ \bullet ha^{-1} \bullet y^{-1}$

PROCESSED

1.5 $t_C \cdot ha^{-1} \cdot y^{-1}$

EtOH Energy Content: 52 $GJ \bullet t_C^{-1}$


Carbon efficiency in soybean biodiesel production
HARVESTED
1.3 $t_C \cdot ha^{-1} \cdot y^{-1}$
PURIFIED
0.38 $t_C \cdot ha^{-1} \cdot y^{-1}$
CAPTURED
3.1 $t_C \cdot ha^{-1} \cdot y^{-1}$
Overall Carbon Yield
0.69 %
Overall Fuel Yield
17 $GJ \bullet ha^{-1} \bullet y^{-1}$
PROCESSED
0.34 $t_C \cdot ha^{-1} \cdot y^{-1}$
FAME Energy Content: 50 $GJ \bullet t_C^{-1}$
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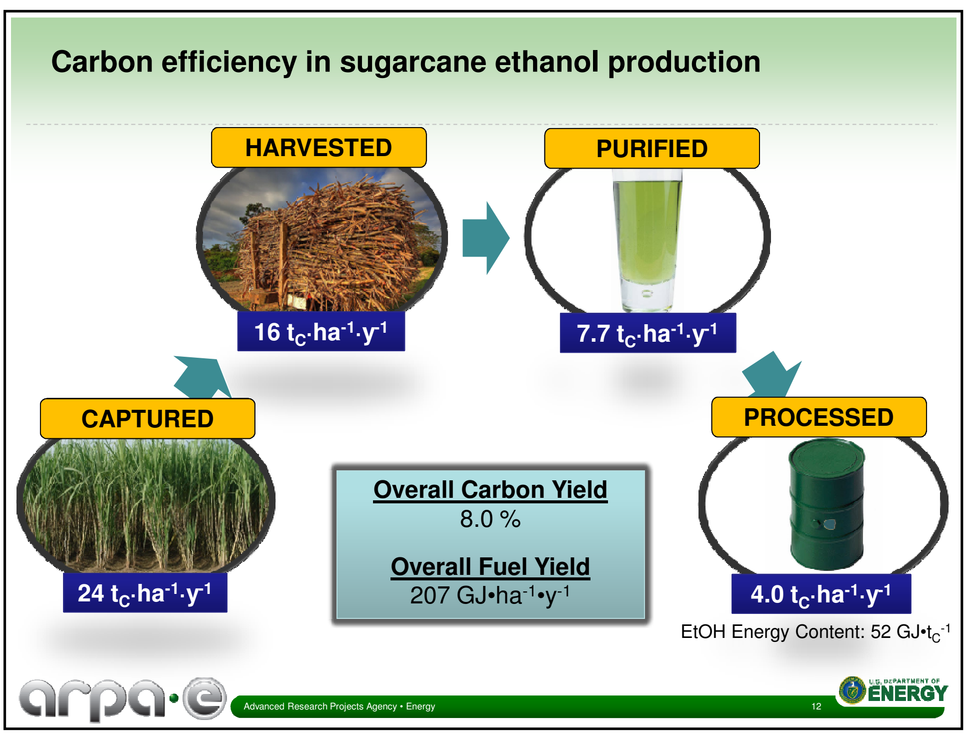
U.S. DEPARTMENT OF ENERGY


Carbon efficiency in sugarcane ethanol production
HARVESTED
16 $t_C \cdot ha^{-1} \cdot y^{-1}$
PURIFIED
7.7 $t_C \cdot ha^{-1} \cdot y^{-1}$
CAPTURED
24 $t_C \cdot ha^{-1} \cdot y^{-1}$
Overall Carbon Yield
8.0 %
Overall Fuel Yield
207 $GJ \bullet ha^{-1} \bullet y^{-1}$
PROCESSED
4.0 $t_C \cdot ha^{-1} \cdot y^{-1}$
EtOH Energy Content: 52 $GJ \bullet t_C^{-1}$
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Sometimes "non-linear" thinking will facilitate the development of the table

	$t_c ha^{-1} yr^{-1}$	Yield
Captured	24	48%
Harvested	16	32%
Purified	7.7	15%
Processed	4.0	8.0%

1
2
3


Sugarcane

$$168.7 \frac{kg\ sucrose}{tonne\ cane} + 152.2 \frac{kg\ dry\ bagasse}{tonne\ cane} = 320.8 \frac{kg\ harvested\ cane}{tonne\ total\ cane}$$

$$168.7 \frac{kg\ dry\ sucrose}{tonne\ cane} + 152.2 \frac{kg\ dry\ bagasse}{tonne\ cane} + 154.4 \frac{kg\ dry\ straw}{tonne\ cane} = 475.2 \frac{kg\ total\ dry\ mass}{tonne\ raw\ cane}$$

$$\frac{320.8 \frac{kg\ harvested\ cane}{tonne\ total\ cane}}{475.2 \frac{kg\ total\ dry\ mass}{tonne\ total\ cane}} = 0.675 \frac{tonne\ harvested}{tonne\ total\ cane\ plant}$$

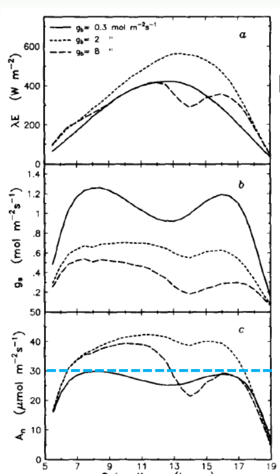
$$101.1 \frac{tonne\ harvested\ cane}{ha * yr} \times \frac{1}{0.675} = 151.0 \frac{tonne\ total\ cane\ plant}{ha * yr}$$

$$151.0 \frac{tonne\ total\ cane\ plant}{ha * yr} \times \left(1 - 0.658 \frac{water\ mass}{tonne\ total\ cane\ plant}\right) = 51.7 \frac{(tonne\ dry\ total\ cane\ plant)}{ha * yr}$$

$$\boxed{51.7 \frac{tonne\ dry\ total\ cane\ plane}{ha * yr} * 0.472 = 24.4\ t_C \cdot ha^{-1} \cdot y^{-1}\ cane}$$

Primary Data in yellow

Theoretical Maximum Photosynthetic Rate ≈ 50 $t_c ha^{-1} yr^{-1}$



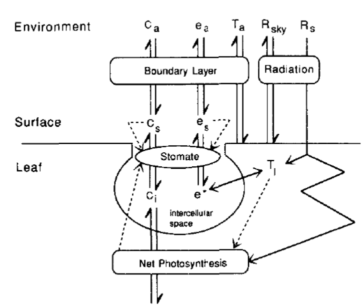
Latent Heat

Stomatal Conductance

Net Photosynthesis

Assumption

Daily average of 30 umol•m^{-2}•s^{-1} based on an average of 12 hours of sunlight per day over an entire year



Source: Collatz, GJ et al. "Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: A model that includes a laminar boundary layer", *Agric. & Forest Meteorology* ***1991, 54, 107-136***

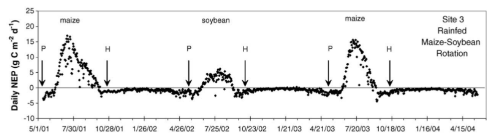
CAPTURED Carbon

Captured[4] $t_c ha^{-1} yr^{-1}$	3.1 (6.3%)

The entire above and below ground plant

Total soybean plant

Ideally, this value is determined from eddy covariance data[4], which has been used here and in our maize calculations.



Source: Verma, S.B. et al. Agricultural and Forest Meteorology *131* (2005) 77–96.

Potentially Useful Resources

- FLUXNET (ORNL)
  - www.fluxnet.ornl.gov
- *A Brief Practical Guide to Eddy Covariance Flux Measurements*
  - *Li-Cor Biosciences, licor.com*

CAPTURED Carbon Calculations

Captured[4] $t_c ha^{-1} yr^{-1}$	3.1 (6.3%)

The entire above and below ground plant

Total soybean plant

…however, most applicants will have to calculate this value from other sources, such as back-calculation from harvested yields, as shown here.

DATA	Ref
Soybean fruit accounts for **20.65%** of plant dry wt	1
Carbon content of soy plant biomass: **42.6 %**	2
3.01 tonne·ha⁻¹·yr⁻¹ max US soybean yield since 1924	3

Total plant biomass back-calculation from harvested yield:

$$3.01\frac{tonne}{ha\cdot yr}\cdot\frac{1}{0.2065}=14.57\frac{tonne}{ha\cdot yr}$$

Carbon content calculation:

$$14.57\frac{tonne}{ha\cdot yr}\cdot\frac{1}{0.426}=6.2\frac{tonne_C}{ha\cdot yr}$$

A rough approximation for the captured yield

Sources: (1) El-Darier, S.; Hemada, M.; Sadek, L. "Dry matter distribution and growth analysis in soybeans under natural agricultural conditions", *Pak. J. Biol. Sci.* **2002**, *5*, 545-549. (2) United Soybean Board, "Life Cycle Impact of Soybean Production and Soy Industrial Products," **2010**, downloaded from: http://www.soybiobased.org/wp-content/uploads/2010/02/Soy-Life-Cycle-Profile_Report.pdf (3) USDA, National Agricultural Statistics Service, **2009** (4) Hollinger, S.E.; Bernacchi, C.J.; Meyers, T.P. "Carbon budget of mature no-till ecosystem in North Central Region of the United States", *Agr. Forest Meterol.* **2005**, *130*, 59-69.

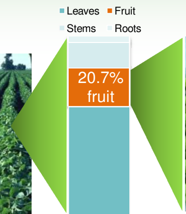
HARVESTED Carbon

Harvested[4] $t_c ha^{-1} yr^{-1}$	1.3 (2.5%)

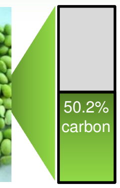
The components of the plant harvested for fuel production

Obtained from eddy covariance data here

Total soybean plant



Raw soybeans



DATA	REF
3.01 tonne·ha^{-1}·yr^{-1} max US soybean yield since 1924	1
76.4% carbon in triglyceride **43.8%** carbon in defatted meal	2
20 % wt of triglycerides in total soybean	3

Potentially Useful Resources

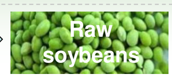
- USDA NASS
  - nass.usda.gov
- EERE Biomass Feedstock Composition and Property Database
  - eere.energy.gov/biomass/feedstock_databases.html
- USDA Extension Planting Guides

Sources: (1) USDA, National Agricultural Statistics Service, **2009** (2) Osborn, T.W. "Elemental composition of soybean meal and interlaboratory performance", *J. Agric. Food Chem.* **1977**, *25*, 229-232. (3) Huber, G.W.; Iborra, S.; Corma, A. "Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering", *Chem. Rev.* **2006**, *106*, 4044-4098. (4) Hollinger, S.E.; Bernacchi, C.J.; Meyers, T.P. "Carbon budget of mature no-till ecosystem in North Central Region of the United States", *Agr. Forest Meterol.* **2005**, *130*, 59-69.

HARVESTED Carbon Calculations

The components of the plant harvested for fuel production

20.7% fruit



50.2% C

Harvested $t_c ha^{-1} yr^{-1}$
1.3 (2.5%)

DATA	REF
3.01 tonne·ha^{-1}·yr^{-1} max US soybean yield since 1924	1
76.4% carbon in triglyceride **43.8%** carbon in defatted meal	2
20 % wt of triglycerides in total soybean	3

$$3.01\frac{tonne}{ha\cdot yr}\cdot 0.20 = 0.60\frac{tonne_{TAG}}{ha\cdot yr}$$

$$3.01\frac{tonne}{ha\cdot yr} - 0.60\frac{tonne_{TAG}}{ha\cdot yr} = 2.41\frac{tonne_{defattedmeal}}{ha\cdot yr}$$

$$0.60\frac{tonne_{TAG}}{ha\cdot yr}\cdot 0.764 = 0.46\frac{tonne_{C}}{ha\cdot yr}$$ In TAG

$$2.41\frac{tonne_{defattedmeal}}{ha\cdot yr}\cdot 0.438 = 1.06\frac{tonne_{C}}{ha\cdot yr}$$ In defatted meal

Back-calculation of total harvested biomass using eddy covariance data:

$$1.259\frac{tonne_{C}}{ha\cdot yr}\cdot\frac{1}{0.502} = 2.51\frac{tonne}{ha\cdot yr}$$

(since we want to use the best available data in "downstream" calculations)

$$0.46\frac{tonne_{C}}{ha\cdot yr} + 1.06\frac{tonne_{C}}{ha\cdot yr} = 1.5\frac{tonne_{C}}{ha\cdot yr}$$ An approximation for the harvested carbon yield

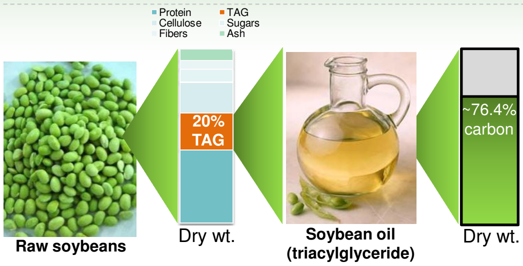
$$1.51\frac{tonne_{C}}{ha\cdot yr}\Big/ 3.01\frac{tonne}{ha\cdot yr} = 50.2\%\ \text{carbon}$$

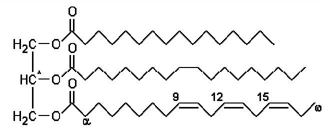
Sources: (1) USDA, National Agricultural Statistics Service, **2009** (2) Osborn, T.W. "Elemental composition of soybean meal and interlaboratory performance", *J. Agric. Food Chem.* **1977**, *25*, 229-232. (3) Huber, G.W.; Iborra, S.; Corma, A. "Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering", *Chem. Rev.* **2006**, *106*, 4044-4098. (4) Hollinger, S.E.; Bernacchi, C.J.; Meyers, T.P. "Carbon budget of mature no-till ecosystem in North Central Region of the United States", *Agr. Forest Meterol.* **2005**, *130*, 59-69.

PURIFIED CARBON

Purified $t_c ha^{-1} yr^{-1}$	0.38 (0.77%)

The chemical components of the harvested material before fuel processing





Representative TAG molecule

DATA	REF
2.51 tonne·ha^{-1}·yr^{-1} soybean biomass	Calculated above in 'harvested'
20 % wt of triglycerides in total soybean	1
~76.4% carbon in triglyceride (weighted average based upon 12% palmitic, 3% stearic, 22% oleic, 56% linoleic, and 6% linolenic constituent fatty acid methyl esters)	2

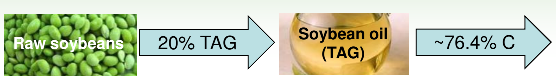
Potentially Useful Resources

- "Thermodynamic Data for Biomass Conversion and Waste Incineration," NIST/NREL (1986)

Sources: (1) Huber, G.W.; Iborra, S.; Corma, A. "Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering", *Chem. Rev.* **2006**, *106*, 4044-4098. (2) Domalski, E.S.; Jobe, T.L.; Milne, T.A. National Institute of Standards and Technology, "Thermodynamic Data for Biomass Conversion and Waste Incineration" **1986**

PURIFIED CARBON Calculations

The chemical components of the harvested material before fuel processing



Purified $t_c ha^{-1} yr^{-1}$
0.38 (0.77%)

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2.51 tonne·ha^{-1}·yr^{-1} soybean biomass	Calculated above in 'harvested'
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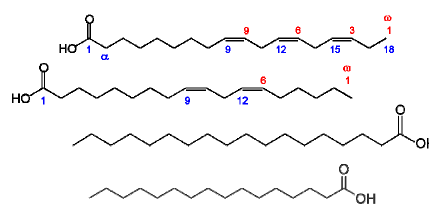


$$2.51\frac{tonne_{soybeans}}{ha\cdot yr}\cdot 0.20 = 0.50\frac{tonne_{TAG}}{ha\cdot yr}$$

$$0.50\frac{tonne_{TAG}}{ha\cdot yr}\cdot 0.764 = 0.38\frac{tonne_{C}}{ha\cdot yr}$$

Assuming TAG carbon ≈ FAME carbon:

FAME	% Comp	# C	# H	# O	Mol Wt	% C	% H	% O
Palmitic	12%	17	34	2	270	75.6%	12.6%	11.9%
Stearic	3%	19	38	2	298	76.5%	12.8%	10.7%
Oleic	22.0%	19	36	2	296	77.0%	12.2%	10.8%
Linoleic	56%	19	34	2	294	77.6%	11.6%	10.9%
Linolenic	6%	19	32	2	292	78.1%	11.0%	11.0%
Wgt Avg	99%				288.62	76.4%		

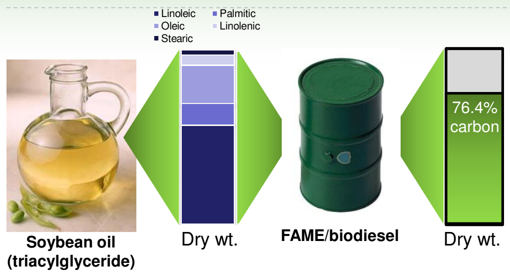
Sources: (1) Huber, G.W.; Iborra, S.; Corma, A. "Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering", *Chem. Rev.* **2006**, *106*, 4044-4098. (2) Domalski, E.S.; Jobe, T.L.; Milne, T.A. National Institute of Standards and Technology, "Thermodynamic Data for Biomass Conversion and Waste Incineration" **1986**

PROCESSED Carbon

The final fuel mixture

Processed $t_c ha^{-1} yr^{-1}$	0.34 (0.69%)

This number will be a projection developed by applicants – it must be justified and relevant assumptions must be reported



DATA	REF
510 L/ha B100	1
0.88 kg/L B100	2
76.4 % carbon in soy FAME mixture (by weight)	Calculation in chart
38 MJ/kg B100 Energy Content (Lower Heating Value)	3

Potentially Useful Resources

- NIST Chemistry Webbook
  - webbook.nist.gov/chemistry/

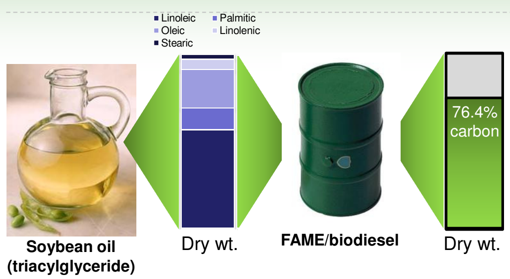
FAME	% Comp	# C	# H	# O	Mol Wt	% C	% H	% O
Palmitic	12%	17	34	2	270	75.6%	12.6%	11.9%
Stearic	3%	19	38	2	298	76.5%	12.8%	10.7%
Oleic	22.0%	19	36	2	296	77.0%	12.2%	10.8%
Linoleic	56%	19	34	2	294	77.6%	11.6%	10.9%
Linolenic	6%	19	32	2	292	78.1%	11.0%	11.0%
Wgt Avg	99%				288.62	76.4%		

Sources: (1) Hill, J.; Nelson, E.; Tilman, D.; Polasky, S.; Tiffany, D. "Environmental, economic,and energetic costs and benefits of biodiesel and ethanol biofuels", *PNAS* **2006**, *103*, 11206-11210. (2) Renewable Biofuels Inc., "Soy Methyl Ester B100" product specification data sheet, from:http://www.rbfuels.com/assets/files/RBF_Soy_Methyl_Ester_B100_Data_Sheet.pdf (3) Bain, World Biofuels Assessment, Milestone Report, NREL/MP-510-42467 December 2007

PROCESSED Carbon

The final fuel mixture

Processed $t_c ha^{-1} yr^{-1}$	0.34 (0.69%)



DATA	REF
510 L/ha B100	1
0.88 kg/L B100	2
76.4 % carbon in soy FAME mixture (by weight)	Calculation in chart
38 MJ/kg B100 Energy Content (Lower Heating Value)	3

$$\boxed{510\frac{L_{B100}}{ha\cdot yr}}\cdot 0.88\frac{kg}{L}\cdot 0.001\frac{tonne}{kg}=0.449\frac{tonne_{B100}}{ha\cdot yr}$$

$$0.449\frac{tonne_{B100}}{ha\cdot yr}\cdot .0764=0.34\frac{tonne_C}{ha\cdot yr}$$

Final Fuel Energy Content ($GJ \cdot t_C^{-1}$):

$$38\frac{MJ}{kg}\cdot\frac{1}{0.764}=50\frac{MJ}{kg_C}=50\frac{GJ}{tonne_C}$$

Sources: (1) Hill, J.; Nelson, E.; Tilman, D.; Polasky, S.; Tiffany, D. "Environmental, economic,and energetic costs and benefits of biodiesel and ethanol biofuels", *PNAS* **2006**, *103*, 11206-11210. (2) Renewable Biofuels Inc., "Soy Methyl Ester B100" product specification data sheet, from:http://www.rbfuels.com/assets/files/RBF_Soy_Methyl_Ester_B100_Data_Sheet.pdf (3) Bain, World Biofuels Assessment, Milestone Report, NREL/MP-510-42467 December 2007

Energy Yield – putting it all together

	$t_c ha^{-1} yr^{-1}$	Yield
Captured	3.1	6.3%
Harvested	1.3	2.5%
Purified	0.38	0.77%
Processed	0.34	0.69%

Overall Fuel Yield ($GJ \cdot ha^{-1} \cdot yr^{-1}$):

$$0.34 \frac{tonne_C}{ha \cdot yr} \cdot 50 \frac{GJ}{tonne_C} = 17 \frac{GJ}{ha \cdot yr}$$

Target for PETRO: $\geq 160\ GJ \cdot ha^{-1} \cdot yr^{-1}$

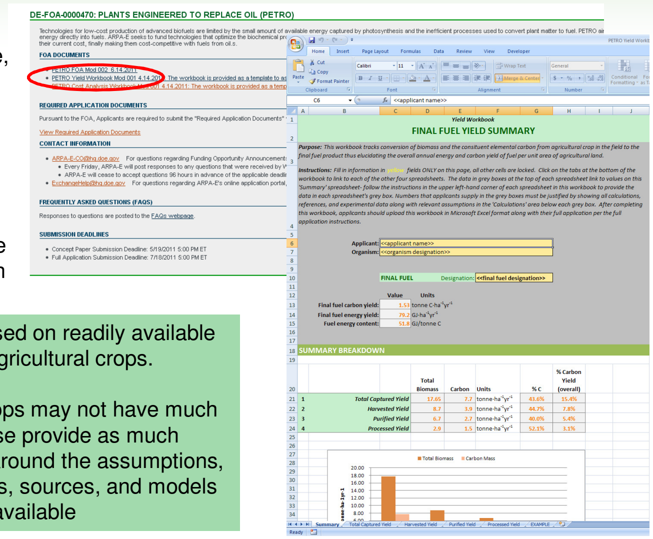
Motivations

Our Process

Your Process

Your process ≈ Our process

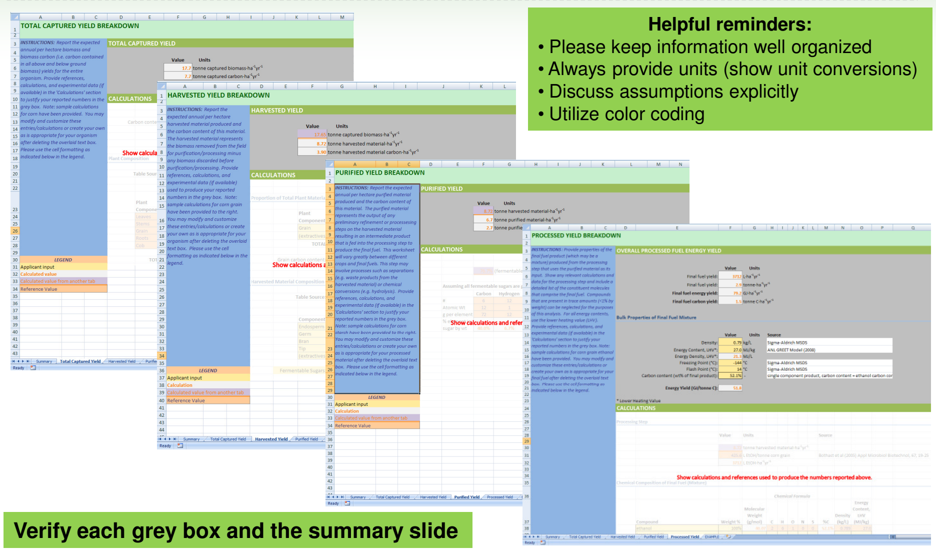
- ARPA-E has provided applicants with a template, the ‘PETRO Yield Workbook’
- Feel free to show all your work and modify any unlocked cells
- The Workbook is a required component of the full application submission



Our calculations are based on readily available data on current agricultural crops.

While your proposed crops may not have much data available, please provide as much information as possible around the assumptions, estimations, experiments, sources, and models that ***are*** available

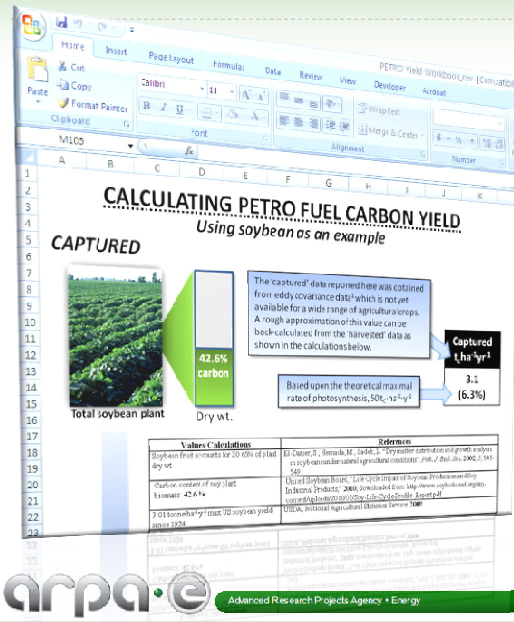
Select each drill down tab and show us your calculations and relevant references



Helpful reminders:
- Please keep information well organized
- Always provide units (show unit conversions)
- Discuss assumptions explicitly
- Utilize color coding

Verify each grey box and the summary slide

Example from above is found in the Yield Workbook



Download from:
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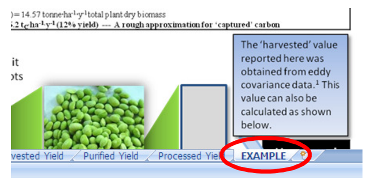

Conclusion

- This concludes the Webinar on the Yield Workbook. As stated in the FOA, all questions must be emailed to ARPA-E-CO@hq.doe.gov.
- All Yield Workbooks must be uploaded with Full Applications

Full Application Due Date : July 18, 2011 5PM ET

ARPA-E recommends submitting all required Full Application materials at least 24 hours in advance of the deadline

- As a reminder, the **Cost Workbook Webinar** will be held at **1-2 PM ET on Wednesday, June 29, 2011**. ARPA-E will provide instructions for accessing and attending this webinar by separate email. If you are unable to attend this webinar, a recording of the webinar will be available until the Full Applications are submitted.
- Thank you for attending the Webinar today! We appreciate your interest in this Funding Opportunity Announcement.